

Are High-Velocity Clouds the Building Blocks of the Local Group?

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Abstract. Motivated by the apparent order-of-magnitude discrepancy between the observed number of Local Group satellite galaxies, and that predicted by Λ CDM hierarchical clustering cosmologies, we explore an alternate suggestion - perhaps the missing satellites are not actually “missing”, but are instead “in disguise”. The disguise we consider here is that of the classical HI High-Velocity Clouds. Is it possible that what have been thought of traditionally as a “Galactic” phenomenon, are actually the building blocks of the Local Group? We discuss the strengths and weaknesses of this hypothesis, and highlight avenues of future research which may provide an unequivocal resolution to this contentious issue.

1. Introduction

A natural byproduct of hierarchical clustering galaxy formation scenarios - perhaps best represented by the currently favoured Λ -dominated Cold Dark Matter (Λ CDM) paradigm - is that our Local Group of galaxies should be populated by ~ 500 satellite objects (e.g. Klypin et al. 1999). This prediction is in (apparent) stark contradiction with the observed Local Group census (~ 30 satellites).

While the above dichotomy makes it tempting to pursue alternatives to Λ CDM, it would be prudent to at least consider the more conservative hypothesis - Λ CDM is correct and we have simply “misplaced” the satellites. Two obvious mechanisms consistent with this hypothesis would be to

1. make the satellites invisible, or
2. disguise the satellites.

Options under mechanism 1 include stripping/ejecting any baryons associated with the CDM halo, perhaps through feedback (Chiu, Gnedin & Ostriker 2001), and/or ionising any residual gas therein, or perhaps through re-ionisation of the Universe not allowing gas to cool into the smallest CDM halos (Moore 2001). In both cases, little accompanying stellar component can exist (or else the satellites would become “visible”). In some sense, mechanism 2 represents the least “radical” of the options and forms the basis of much of the subsequent discussion.

To date, the best suggested “disguise” for these supposed missing satellites is that worn by the population of High-Velocity Clouds (HVCs). HVCs are traditionally classified as HI gas clouds whose velocities are inconsistent with that of Galactic rotation (e.g. Wakker, van Woerden & Gibson 1999). Since their discovery 40 years ago, debate concerning their origin has ranged from the local (Galactic fountain), to the intermediate (tidal disruption of accreting

dwarfs), to the distant (Λ CDM building blocks left over from the formation of the Local Group). Blitz et al. (1999) and later Braun & Burton (1999), revived this extragalactic scenario,¹ and have both provided persuasive arguments to support their cases (see also Blitz 2001; Burton et al. 2001). With ~ 2000 HVCs now catalogued (Putman et al. 2001), their numbers are certainly a good match to the predicted number of Λ CDM halos. Shortcomings to this picture have been highlighted by Gibson et al. (2001ab), Weiner et al. (2001), Zwaan (2001), Charlton et al. (2000), and Combes & Charmandaris (2000), amongst others.

In what follows, we discuss several arguments which have been employed to support (or refute) the extragalactic HVC scenario, drawing attention to ongoing (and future) programs designed to shed light on this contentious issue.

2. The Evidence ...

In terms of discriminating between the extragalactic (Λ CDM) and Galactic (fountain or dwarf galaxy tidal disruption) origin scenarios for HVCs, any number of *indirect* arguments can be made, but in actuality, only one, clean, *direct* discriminant exists - HVC distance.

2.1. Distances

Under the Λ CDM scenario, HVCs are presumed to populate the Local Group, with typical distances of ~ 700 kpc; in contrast, both the Galactic fountain and dwarf galaxy disruption scenarios favour distances of order ~ 10 kpc. In theory, this (approximate) two orders-of-magnitude difference offers a clean discriminant between the models. In practice, despite distance being this “Holy Grail”, its determination is *extremely* challenging.

The only bona fide mechanism for setting a useful HVC distance bracket (or an upper limit) is via absorption line spectroscopy towards background halo stars of known distance. As stressed by Wakker (2001) and Gibson et al. (2001a), the dearth of suitably bright and distant, blue-horizontal branch halo stars aligned with the high HI column density cores of HVCs,² has limited the successful³ application of this technique to just five HVCs.⁴ **All five of these HVCs lie clearly in the Galactic halo**⁵ Gibson et al. (2001a; Table 1).

¹In contrast with Blitz et al. (1999), Braun & Burton (1999) eliminate all extended ($\gtrsim 1^\circ$) HVCs, and consider only Compact HVCs (CHVCs) to be associated with residual Λ CDM halos.

²We are undertaking a program at the United Kingdom Schmidt Telescope, in an attempt to rectify this shortcoming. We (in collaboration with Mike Bessell, Tim Beers, Norbert Christlieb, John Norris, and Joss Bland-Hawthorn) are employing the 6dF facility to take intermediate-resolution spectra of Hamburg/ESO Survey and Beers/Preston HK Survey candidate B-HB halo stars, prior to followup high-resolution work for the best HVC probes.

³“Success” defined here as a clear halo vs non-halo residency determination for the given HVC.

⁴The marginal detection of an HVC in Complex WD, seen in absorption against a halo RR Lyrae at 5 kpc (Comeron 2000, priv comm), needs confirmation, particularly in light of its projected location near the Local Group’s anti-barycentre.

⁵Despite Blitz’s (2001) protestations, HVC 100–7+100 is both an HVC - its positive velocity is significantly inconsistent with that expected by Galactic rotation in this quadrant - and its

While it might be tempting to succumb to hyperbole and claim the HVC mystery solved, since all five for which a halo vs non-halo status could be determined clearly reside in the Galactic halo, it's crucial to bear in mind that (i) we are still only talking about $\sim 1\%$ of the known HVCs, and (ii) an unavoidable selection effect plagues this interpretation, in the sense that there simply aren't any background halo stars out at $\gtrsim 500$ kpc with which to probe HVCs at (putative) comparable distances. *If* it could be shown that gaseous HVCs are accompanied by an associated stellar population, it is not inconceivable that deep, targeted, searches for the tip of the red giant branch (or maybe RR Lyrae) might provide a useful distance determination for intra-Local Group HVCs. Using the LCO and KPNO, Grebel et al. (2000) are searching for RGB stars in several CHVCs, and while they have several candidates, the data do not show convincing evidence for the presence of significant numbers of stars. Unequivocal conclusions are complicated by the potential confusion with unresolved, background, starburst galaxies. 8-10m class spectroscopic confirmation for all candidates is a necessity. Josh Simon, as part of his PhD at Berkeley, has also been cross-correlating hundreds of HVCs with POSS-II plates.⁶

While the absorption line and tip of the RGB techniques are classified as *direct*, they are applicable to only a handful of HVCs. That said, there are several *indirect* methods which can be applied to (potentially) hundreds of HVCs.

The indirect technique which has received the most attention over the past few years is that based upon $H\alpha$ emission (Bland-Hawthorn & Maloney 1999). As shown by Bland-Hawthorn et al. (1998), Tufte et al. (1998), and Weiner et al. (2001), HVCs are detected regularly in $H\alpha$ emission, with a subset seen in low ionisation lines. Under the (reasonable) assumption that $\gtrsim 1\%$ of the Galaxy's ionising photons escape the disk, coupled with models governing the distribution of this ionising field, covering fraction, topology, and line-of-sight orientation, an HI screen at a given distance will result in a specific $H\alpha$ emission measure. The original halo radiation field of Bland-Hawthorn & Maloney assumed an underlying exponential disk for the Galaxy. While valid in the far-field limit, this model broke down within ~ 10 kpc of the disk, where the proximity to spiral arms is important (and where we know many HVCs lie). However, as reported at this meeting, most failings of the preliminary model have been rectified by incorporating a proper treatment of spiral arms (Bland-Hawthorn et al. 2001). All known HVCs, with both measured $H\alpha$ emission and absorption line distance constraints, are now consistent with the predictions of this spiral arm $H\alpha$ model, and appear to lie within ~ 100 kpc of the Galaxy; to date, this indirect technique does *not* support the intra-Local Group predictions of Blitz et al. (1999) and Braun & Burton (1999). What remains true however, is that $H\alpha$ detections of the Magellanic Stream are perplexingly bright, and re-

existence confirmed in both HI (Bates et al. 1991) and the ultraviolet (Bates et al. 1990). Its low column density - $N(\text{HI}) = 3 \times 10^{18} \text{ cm}^{-2}$ - is what makes it difficult to extract from the Leiden-Dwingeloo Survey data, and not its non-existence!

⁶We are involved in several deep searches for stars in CHVCs, involving the 6.5m Baade Telescope and (hopefully!) the 4m Anglo-Australian Telescope. Those involved in the collaborations include Dan Kelson, Wendy Freedman, Geraint Lewis, Rodrigo Ibata, and Joss Bland-Hawthorn.

quire at least one additional (unidentified) ionising source (Weiner et al. 2001; Bland-Hawthorn et al. 2001).

Employing thermal pressure arguments pertaining to CHVCs,⁷ Burton et al. (2001) claim that CHVCs lie at a distance of 400 ± 280 kpc. As emphasised to us by Amiel Sternberg (2001, priv comm)⁸ though, distance estimates based upon eqn 4 of Burton et al. are technically only upper limits. Their argument is predicated upon the assumption that the thermal pressure (P) equates to the minimum pressure (P_{\min}) required at the core/halo interface. However, the condition for a multiphased mixture is that $P_{\min} < P < P_{\max}$; P could be significantly larger than P_{\min} and still be consistent with cold and warm neutral media (provided, of course, that $P < P_{\max}$). Even these upper limits are uncertain, since the value of P_{\min} depends upon the assumed shielding column and there is no *a priori* reason to adopt $1 \times 10^{19} \text{ cm}^{-2}$ (as was used by Burton et al.).

HVC 165–43–120 is part of the Anti-Centre High-Velocity complex mapped in HI by Cohen (1981), and H α by Weiner et al. (2001). The Cohen “Stream” at -110 km/s spans 25° on the sky and traces a parallel filament clearly associated with the local ISM at -13 km/s. Cohen suggests the -110 km/s must therefore be colliding with the Galactic disk at a distance of ~ 300 pc. This Stream is akin to the family of HVCs which show direct connections to Galactic gas (Putman & Gibson 1999), and therefore must be relatively nearby.

Building upon the observation that a large number ($\sim 20\%$) of CHVCs show compression-front and tail-shaped features, suggestive of interaction with an external medium, Quilis & Moore (2001) have performed 3D-hydro simulations which are consistent with the data, but only for ambient densities $\gtrsim 10^{-4} \text{ cm}^{-3}$. Such densities are not consistent with that expected in the intergalactic medium. These simulations suggest that $\gtrsim 20\%$ of CHVCs reside in the halo of our Galaxy.

In summary, those HVCs which possess useful *direct* distance constraints all reside within the halo of the Milky Way. Similarly, *indirect* distance measurements based upon H α emission, relation to Galactic disk HI, and head-tail substructure, are also consistent with a halo residency.

2.2. Metallicities

While HVC distance is the cleanest discriminant between Galactic *fuel* and galactic *waste* scenarios, metallicity also offers a potentially useful, albeit indirect, indicator. Under the Blitz et al. (1999) and Braun & Burton (1999) scenarios, HVCs (or at least CHVCs) can be considered to be remnants (or building blocks, or perhaps “failed” dwarfs) of the formation of the Local Group. Blitz et al. suggest that metallicities $\lesssim 0.2 Z_\odot$ are consistent with their model. If HVCs really are failed dwarfs, though (or accreting remnants of the early phases of the Local Group), one might expect their metallicities to be $\lesssim 0.01 Z_\odot$, since such metallicities are encountered in the dwarf spheroidals (dSphs) of the Local Group. However, as summarised by Gibson et al. (2001a), the majority of HVCs

⁷Specifically, the physical conditions necessary for the establishment (and maintenance) of cold neutral cores embedded within warm neutral halos.

⁸Details are provided in their forthcoming paper (Sternberg et al. 2001).

appear to have metallicities of $\sim 0.3 Z_{\odot}$, subject to the usual caveats concerning ionisation and dust corrections, as well as small-scale HI sub-structure.

Inspection of Figure 1 illustrates dramatically the discrepancy between HVC metallicities (upper boxed region) and metallicities of the lowest luminosity components of the Local Group (lower boxed region). If HVCs really are Local Group building blocks, they are clearly very different from the dSphs we currently see.

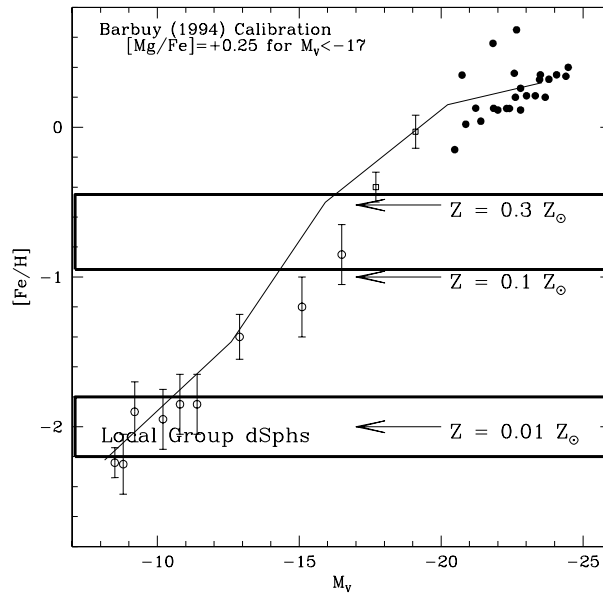


Figure 1. Spheroidal galaxy metallicity-luminosity relation, adapted from Gibson (1997). Local Group dwarf spheroidals, akin perhaps to the Group’s original building blocks, show metallicities of $\sim 0.01 Z_{\odot}$ (lower boxed region), while HVCs show values in the range $\sim 0.1 \rightarrow 0.3 Z_{\odot}$. **HVCs today do not resemble Local Group building blocks such as low luminosity dwarf galaxies.**

HVC Complex C deserves a few words, as it has been put forth as the most likely candidate to be the low-metallicity infalling Galactic fuel required by chemical evolution models aiming to avoid the so-called “G-dwarf problem”. This problem is the (generally) unavoidable overproduction of low-metallicity stars in closed-box models of the Galaxy’s evolution. Wakker et al. (1999) derived a metallicity of $0.09 Z_{\odot}$ based upon the Mrk 290 sightline through Complex C, and suggested this HVC was this infalling Galactic star formation fuel. This interpretation has since been clouded by the analysis of Gibson et al. (2001b), who show that abundances as high as $\sim 0.3 Z_{\odot}$ are encountered along the Mrk 817 sightline. As noted by Tosi (1988), infalling gas metallicities $\gtrsim 0.2 Z_{\odot}$ lead to a present-day disk gas-phase oxygen gradient which is inconsistent with that observed. We have returned to this issue with our new dual-infall model for Galactic chemical evolution, employing `GEtool`, a new Galaxy Evolution tool under development at Swinburne (Fenner & Gibson 2002). Our results strengthen the conclusions of Tosi, not only through the oxygen gradients, but also the G-dwarf distribution, age-metallicity relation, and gas surface density constraints. Preliminary results are shown in Figure 2, with full details to be provided in Chiappini et al. (2002).

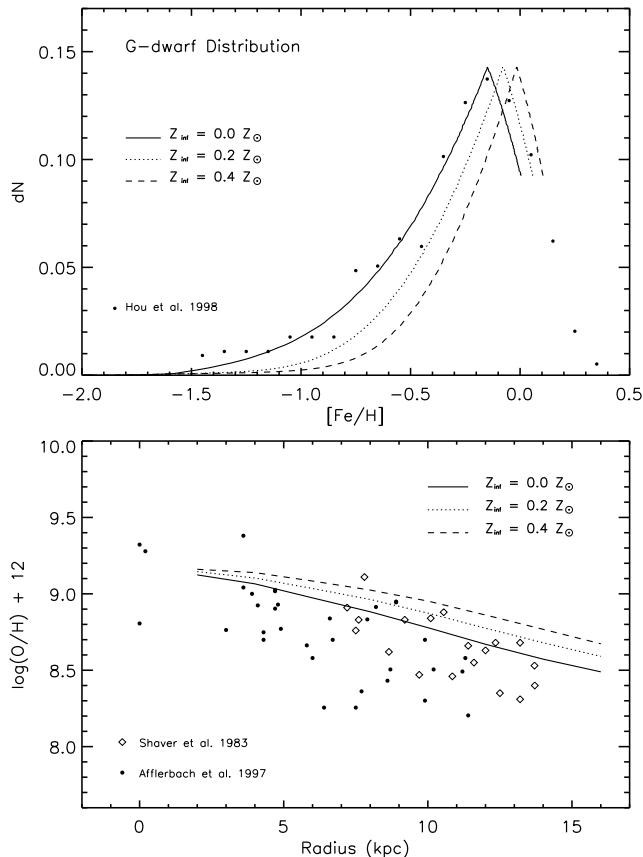


Figure 2. *Upper:* Solar neighbourhood G-dwarf distribution - symbols represent the observed data, while curves correspond to model predictions from **GETool** (Fenner & Gibson 2002), each of which employed a different metallicity for the infalling gas (Z_{inf}) in the disk-phase of our dual-infall simulations. **Metallicities greater than $\sim 0.1 Z_{\odot}$ are difficult to reconcile with the observed G-dwarf distribution.** *Lower:* Present-day Milky Way radial oxygen abundance profile predicted by our dual-infall phase chemical evolution model. Observed abundances in HII regions are represented by symbols, while the curves indicate model predictions for disk-phase infalling gas with primordial (solid line), 20% solar (dotted line) and 40% solar (dashed line) metallicity. All models assume primordial composition for the halo-forming gas. The three models satisfy the observed slope, although **each increase in metallicity shown here is accompanied by a 0.1 dex increase in zero point.** The mild overproduction of oxygen, even in the case of primordial infall, is a common aspect of Galactic chemical evolution models.

The fact that most HVCs have metallicities of $\sim 0.3 Z_{\odot}$ led Gibson et al. (2001a) to conclude that not only was this inconsistent with the Blitz et al. (1999) and Braun & Burton (1999) pictures, but also with the classical Galactic Fountain picture (in which metallicities near solar might be expected). While we are still of that opinion, the conclusion should perhaps be tempered by the bottom panel of Figure 2. *If* HVCs originate from a fountain at a Galactocentric distance ~ 5 kpc (location of the disk’s present-day star formation maximum), metallicities in the range $\sim 0.6 \rightarrow 1.3 Z_{\odot}$ would be expected (“solar” being $\log(O/H)+12=8.9$); *if* HVCs originate near the solar circle ($\sim 6 \rightarrow 12$ kpc), the range would extend to $\sim 0.2 \rightarrow 1.2 Z_{\odot}$. These ranges are, technically, upper lim-

its, as dilution from near-pristine halo gas will push the values down somewhat. The point we wish to make here is that the *occasional* metallicity as low as $\sim 0.2 Z_{\odot}$ does not sound the death-knell for the Galactic Fountain; that said, persistent values this low are difficult to reconcile with a Galactic origin, unless dilution by metal-poor halo gas is extremely efficient.

The next 12 months will see Complex WD (toward the Local Group’s anti-barycentre) come under scrutiny,⁹ lengthy revisits to Complex C,¹⁰ the Mrk 205 HST/STIS analysis of Bowen et al. (HST PID#8625),¹¹ and the first useful upper limit on the metallicity of a CHVC (Sembach et al. 2001).

2.3. Kinematics

As discussed in Gibson et al. (2001a), arguments in support of an intra-Local Group residency for HVCs, based upon the velocity distribution (both its centroid and dispersion) being more “favourable” in the Galactic or Local Group Standard of Rest (as opposed to the Local Standard of Rest) are somewhat specious. This is a necessary, but *not* sufficient, condition; *any* model which results in the appropriate sinusoidal behaviour in the ℓ - v_{LSR} plane, which includes many Galactic fountain and Magellanic Cloud disruption scenarios, will result in a decreased velocity dispersion in the GSR and LGSR frames.

The number of catalogued HVCs below $\delta = +0^{\circ}$ has now grown to ~ 2000 , with $\sim 10\%$ alone classified as CHVCs (Putman et al. 2001). It should be noted though, that approximately half of the original Braun & Burton (1999) CHVCs which lie in the Putman et al. overlap region have lost their “compact” status, and have been reclassified (due to the improved spatial resolution used by Putman et al., and a stricter classification scheme). Of further interest, the 179 Putman et al. CHVCs are *not* distributed randomly, but are in fact clustered into three primary groups which lie within $\pm 25^{\circ}$ of the Galactic Plane, or near the South Galactic Pole. The Putman et al. HVCs *and* CHVCs have nearly identical v_{GSR} and v_{LGSR} centroids. Whether that means both HVCs and CHVCs therefore have the same origin remains unresolved.

We wish to comment upon the size-linewidth analysis of Combes & Charmandaris (2000). These authors show that those HVCs which are *known* to reside in the Galactic halo, adhere to the molecular cloud size-linewidth relation. Further, they note that the Braun & Burton (1999) CHVCs would also follow this relation, *if they had typical distances of 20 kpc*. Invoking Occam’s Razor, Combes & Charmandaris suggest therefore that most CHVCs are not of an extragalactic nature. While interesting, and possibly correct, this conclusion should be tempered with the knowledge that dark matter dominated Local Group objects (such as the aforementioned dSphs) do not follow this self-same relationship. Taken one step further, if CHVCs are also in fact dark matter dominated entities (as both Blitz et al. 1999 and Braun & Burton 1999 argue),

⁹Including our FUSE Cycle 2 GI program, in collaboration with Mark Giroux.

¹⁰Including several HST GI programs led by Bart Wakker and David Bowen, as well as the FUSE Science Team’s ongoing analyses.

¹¹Mrk 205 intersects both Complex C and CHVC 125+41–207; the Bowen et al. data should provide the first useful metallicity determination for a CHVC.

then there would be no *a priori* reason to force them to follow the Galactic molecular cloud size-linewidth relation.

2.4. Association with Extra-Local Group Systems

Some of the more compelling arguments against the Blitz *et al.* (1999) and Braun & Burton (1999) scenarios are due to Zwaan (2001) and Charlton *et al.* (2000). Both teams surveyed nearby Local Group analogs in an attempt to ascertain how common intragroup gas clouds are elsewhere. Charlton *et al.* show that the statistics of MgII and Lyman limit absorbers in the spectra of background QSOs are in disagreement with the extragalactic HVC scenarios. Zwaan surveyed $\sim 4 \text{ Mpc}^2$ of five nearby Local Group analogs, down to an HI mass of $7 \times 10^6 M_\odot$ (4.5σ), also finding no intragroup clouds.¹² The proposed HIPARK Survey at Parkes (led by Frank Briggs, with Martin Zwaan, David Barnes, and us) would have a 6σ detection limit at 6 Mpc of $1 \times 10^6 M_\odot$, covering $\sim 200 \text{ deg}^2$, and would offer more than an order of magnitude improvement over any of the existing extra-Local Group surveys.

An issue which has not received fair attention, but one which remains a tantalising one nevertheless, is the observation that the incidence HVC “activity” in isolated spirals is directly related to the underlying star formation rate (Schulman *et al.* 1997). This certainly seems to be an important clue in the HVC “mystery”, but one which has received scant attention in the recent literature.

2.5. Magellanic Stream

The disruption of the Magellanic Clouds has long been recognised as a potentially crucial component of any complete HVC origin theory (e.g. Wakker 1990; Ch. 5). The discovery of the Leading Arm Feature (LAF), counterpart to the trailing Magellanic Stream, demonstrates that strong tidal forces are involved in disrupting our nearest neighbours (Putman *et al.* 1998). Of further interest is the discovery that the Magellanic Stream is not confined to the canonical linear HI stream. As Gibson *et al.* (2000) show, gas associated with the Stream is seen in MgII along the III Zw 2 sightline; this has since been supplemented by the detection of the Stream in Ly β in FUSE observations of Mrk 335. Coupled with NGC 7469, we now have three clear detections of the Stream in the vicinity of the MS V concentration (Figure 3). FUSE has observed many other sightlines which project onto Figure 3 (and elsewhere in the vicinity of the Stream); examining these data for other Ly β Stream “signatures” will be necessary in order to assess the true extent of disrupted gas from the Magellanic Clouds. We are currently pursuing high-resolution N-body + SPH simulations of the formation and evolution of the Stream, LAF, and associated “disrupted” gas from the Clouds.

2.6. Alternatives to Λ CDM

When all else fails, should the HVCs and CHVCs not correspond to Λ CDM halos, we may be faced with the prospect of venturing outside the confines of standard hierarchical clustering scenarios. Both Warm Dark Matter (WDM) and Self-Interacting Dark Matter (SIDM) offer potentially viable mechanisms

¹²Counter-arguments have been presented by Blitz (2001).

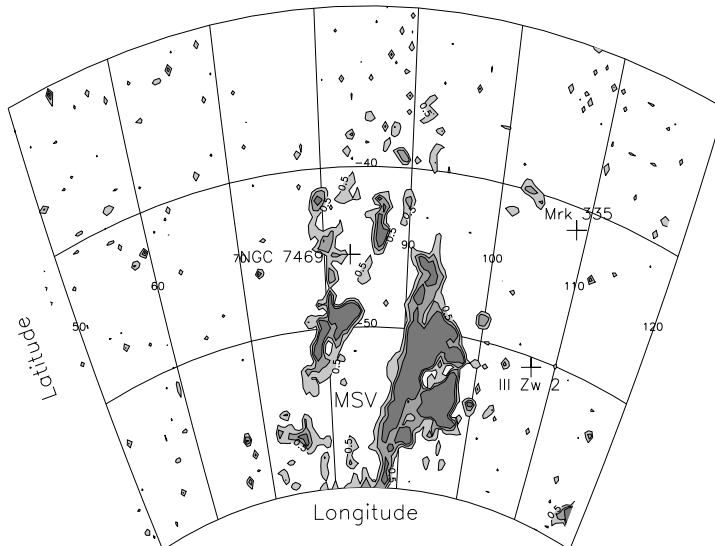


Figure 3. Leiden-Dwingeloo Survey HI map of the MS V concentration within the Magellanic Stream. Beyond the confines of the classical HI filament, the Stream has been detected in ultraviolet absorption towards NGC 7469, III Zw 2, and Mrk 335 - more than 20 kpc (projected) from the canonical Stream!

for suppressing power at small scales. That said, two of the best related analyses invoking WDM (Bode et al. 2001) and SIDM (Davé et al. 2001) show that low-mass halo suppression is limited to factors of a few, as opposed to the orders-of-magnitude required to reconcile theory with the Local Group galaxy distribution. Perhaps the solution retains Λ CDM, but involves an efficient treatment of feedback, à la Chiu et al. (2001). The latter suppress low-mass gas halo production with “physics”, without suppressing the number of dark halos.¹³

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¹³This simulation was not evolved beyond redshift $z=4$, and so questions remain concerning the clustering properties at redshift $z=0$.

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